Calculation of Total Erosion in the Lower Reaches of Mezhdurechensk Reservoir Using Empirical Morphometric Dependencies

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Abstract. The research aims are to develop a methodology and the choice of initial formulas for calculating channel deformations in the lower reaches of waterworks on rivers composed of easily eroded soils (like the Amu Darya river). To calculate the total erosion below the Mezhdurechensk reservoir, both theoretical equations of channel deformation (Saint-Venant equations) and empirical dependences of the transporting capacity of the flow (turbidity) and morphometric dependences of the connection of the width of the deformable channel from the average depth obtained for the lower reaches of the Takhiatash hydrounit, the stem of which is located slightly above the Mezhdurechensk hydrounit, were used. A hydrological series of years was formulated for the calculation (considering the actual frequency of low-water, medium-water, and high-water years). The results of calculating the total erosion of the bottom in the first ten years of the simulated hydrological series of years, provided that the width of the channel in the lower reaches is constant, is expected to be 0.17-0.41 m (with full flow clarification) and 0.16-0.38 m (with partial flow clarification $\varepsilon = 0.8$). The change in the cross-sectional area of the riverbed will be 304(292)m^2. Provided that the width narrows to a stable width $B_{stable} = kh^a$: $\Delta z = 0.41$ m (with the concentration of the flow at a narrower width, the decrease will be correspondingly large). The proposed methodology can be applied to calculate the total erosion on rivers composed of easily eroded soils and having average slopes of the longitudinal profile of the river within 0.0001 (similar to the Amu Darya River).

1 Introduction

The riverbed process as a product of the interaction of water flow with a transporting (and, accordingly, eroding) ability and a channel with varying degrees of resistance to erosion is a complex phenomenon. Calculations and forecasts of channel re-formations in the waterworks after flow regulation are particularly difficult.

The practical application of the theory of the channel process is to assess the course of channel transformations [1,2], calculations of channel deformations [3,4,5], forecasts, and

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identification of general trends in the process [6,7,8]. The riverbed process is a complex physical phenomenon of the process of active interaction of a water flow having a blurring ability [9] and a deformable riverbed. The result of the riverbed process is riverbed reformation, the nature of which depends on many factors. And first of all - the hydrological and alluvial regime [10]. The main channel–forming factors are the flow rate (in conditions of uniform movement - the slope of the bottom) and the characteristics of the soils composing the banks and the bottom of the channel [11,12,13]. In the upper reaches of rivers, where the slopes are relatively large and, accordingly, the flow velocities and the transporting capacity of the flow are high, erosion will be the predominant type of deformation. In the lower reaches of rivers, where the slopes are relatively smaller, siltation will be the predominant type of channel process. The riverbed process is especially intense on rivers composed of easily eroded soils [14,15]. These types of rivers include the Amu Darya River [16,17,18]. An important role like the riverbed process is played by the factor of flow regulation by water support structures. The construction of dams on rivers dramatically changes the natural regime: siltation processes are activated upstream due to a decrease in flow rates in the reservoir, and downstream, there will be a general erosion due to the clarification of the flow coming from the upstream [19,20]. Channel re-formations in the streams of river waterworks have a significant impact on the life of the population living in coastal areas, on ensuring the normal operation of the waterworks and their performance of their functional tasks [21,22]. Therefore, the issues of calculation and prediction of channel deformations in conditions of regulated runoff are of great importance and relevance.

Therefore, the purpose of the research conducted within the framework of this article is to choose a method for calculating the total erosion on rivers composed of easily eroded soils (similar to the Amu Darya River).

To achieve this goal, it is necessary to solve the following tasks:

- selection of the methodology and initial formulas for calculating the total washout.
- to calculate the total washout on a specific object.

The subject of research is methods for calculating the total erosion on rivers composed of easily eroded soils. The object of research is the Mezhdurechensk reservoir on the Amu Darya River.

Currently, there are two main directions in the theory of channel processes applied: theoretical and empirical [6,23,24,25]. The first direction is based on theoretical equations (fluid motion, suspended flow, deformation equations, etc.). The theoretical direction is preferable from the point of view of "revealing" the phenomenon (mechanism) of the channel process, and explaining the processes taking place, according to the rigor of the theoretical justification. But unfortunately, they have not been widely used on the Amu Darya River. Attempts to use them give too large discrepancies with the full-scale data of the general erosion of the channels. They successfully solve narrow problems when there is a limited range of initial and boundary conditions. Empirical methods, unlike theoretical ones, are not based on theoretical equations that reveal the mechanism of the phenomenon. They are based on empirical (morphometric) dependencies that express the relationship between the parameters of the characteristics of the channel parameter. Therefore, there is currently no universal method for calculating channel deformations in the waterworks of a hydroelectric facility. Each researcher should choose the calculation method himself, depending on the specific conditions and tasks. For the conditions of the Amu Darya River, the methods of the empirical direction have been more used [18,22,24].

2 Methods

The methodology of the conducted research consists of applying general scientific research methods within the framework of comparative, logical, and statistical analysis, as well as through the analysis of structure and dynamics, graphical interpretation of calculation results, etc. The general scientific method consisted of analyzing literature on the research problem, generalization, comparison, and systematizing empirical and theoretical data. Theoretical (analysis, synthesis, generalization) and empirical (results of field observations, methods of mathematical processing) methods were used.

To calculate the total erosion below the Mezhdurechensk reservoir, theoretical equations of channel deformation (Saint-Venant equations) were used to solve which empirical dependences of the transporting capacity of the flow (turbidity) and morphometric dependences of the relationship between the width of the deformed channel and the average depth were applied.

The research used materials from the department of riverbeds of the Central Asian Research Institute of Irrigation (Research Institute of Water Problems and Irrigation) [1,15,22] and the Department of "Water Energy Use and Pumping Stations" of the National Research University of "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers" [4,15,26]. The Department of "Water Energy Use and Pumping Stations" conducts research in the field of hydraulic engineering and hydropower [27,28,29], as well as hydraulics, hydrology, and riverbed processes.

The Mezhdurechensk reservoir is formed between the channels of the Amudarya River — Akdarya (eastern channel) and Kipchakdarya (western channel) by the construction of earthen dams and is intended to meet the n/a needs of the population and territories of the adjacent Muynak district.

When calculating the total erosion below the Mezhdurechensk reservoir, we used an improved method for calculating channel deformations in the lower reaches of the GTS, which takes into account several specific features inherent in the Amu Darya River [1,15].

The method is based on strict theoretical equations of hydraulics and channel deformation (Saint-Venant's equations), which are supplemented by:

1) morphometric dependence between the average depth of the riverbed and the width along the cut of S.T. Altunin. The empirical coefficients k and h are refined based on extensive hydrometric data downstream of the Takhiatash hydrosystem. For the calculation, we take:

$$B=kh^{\alpha}=300h^{0.4}. \qquad (1)$$

2)) the formula for determining the average turbidity of the flow S_{aver} obtained as a result of statistical processing of hydrometric data on the Samanbai g/p for 1974-79 (the initial period of operation of the hydrosystem:

$$S_{aver} = 0.11\ (V^{1.5}/(ghw)^{0.5}); \qquad (2)$$

3) when deriving the initial equations, a linear change in the flow rate along the length and a change in the width of the flow depending on the depth were taken into account;

4) for the preliminary assignment of the degree of clarification of the flow coming from the upstream, the formula for the distribution of average turbidity along the length of the washout section is used;

5) an algorithm and a program in the language "Turbo Pascal 7.0" have been compiled for the calculation.

The volume of the Mezhdurechensk reservoir is 200 million m^3. The Northern dam is being restored at 58.0. The side spillway is reconstructed at 56.0, has a length of 1800 m, and is made in the form of a spillway with a wide threshold at 56.0 m from precast reinforced concrete slabs and is designed to pass a flood of 3700 m^3/s at 57.0 m.

For calculations, the following are accepted:

a) as low-water: the actual 2011 and two calculated ones, modeled on hydrographs of 2003 and 2006.

b) average years: actual 1997 (P=54%), 2007 (P=45%), 2009 (P=37%).

c) the hydrograph of 2001 was adopted as a high-water one (P=14%).

Based on hydrograph data, discharges from the Mezhdurechensk reservoir through a side spillway were calculated (Table 1.)

The calculation is carried out for two gates: gate 1 is 200 m below the lateral spillway and has a fixed width along the edge equal to the spillway front of the dam B_1 = 1800 m, i.e., it contradicts the morphometric dependence. So, to avoid this contradiction, the concept of "given the depth and width" must satisfy the condition: $\omega_{given}=\omega_1$, i.e., $B_{given} = kh^{\alpha}_{given}$ where $h^{\alpha+1}_{given} = (B_1 h_1)/k$ or $h_{given} = \sqrt[\alpha+1]{(B_1 h_1)/k}$.

Table 1. Data on the actual discharge of water through the spillway Mezhdurechensk reservoir (flow (million m^3) / flow (m^3/s))

Years, months	calculated low- water 1993	calculated low-water 1996	actual low-water 2001	actual mid-water 1997	actual mid-water 2007	actual mid-water. 2011	actual high- water 2003
I	—	—	13 / 36	228/612	296 /794	124/333	293/789
II	—	—	—	123/298	110/267	31/75	156/376
III	—	—	—	—	67/180	43/114	39/105
IV	—	—	—	—	—	—	46/120
V	78/ 208	—	—	—	—	—	135/362
VI	—	—	—	—	—	—	255/661
VII	—	—	—	—	—	—	149/400
VIII	—	—	—	—	—	46/123	224/599
IX	—	8 / 20	—	41 / 107	—	138/157	580/1501
X	—	—	—	10 / 26	10/27	203/560	550/1473
XI	—	—	—	—	24/61	83/215	162/419
XII	—	—	—	—	12/32	123/329	41/109
annual	7 / 208	0,6/ 20	1 / 36	33/1043	43/1361	67/2106	219/6911

The gate 2 is located X m below the spillway. Hydraulic and geometric parameters were calculated by morphometric dependence (1) and by the formulas of hydraulics (Shezi):

$$Q = C*\omega \sqrt{(R*i)}\ ; \tag{3}$$

where $C = (1/n) R^{m1}$; n is the roughness coefficient; m_1 is the hydraulic indicator of the riverbed; i is the slope of the watercourse; $\omega = B_2 h_2$ is the area of the cross-section of the riverbed;

When calculating the depths in the alignment 1, a general method of constructing a free surface curve using a simplified form of the curve equation was used (losses on local resistances and the influence of velocity pressure are not taken into account):

$$z_m - Q^2 \frac{1}{K^2_{aver}} = z_{m+1}\ , \tag{4}$$

where z_m, z_{m+1} are marks of the free surface in the gates m and *(m+1)*; ℓ is the distance between the gates; *K* is discharge characteristic.

$$\frac{1}{K_{aver}^2} = \frac{\frac{1}{K_m^2} + \frac{1}{K_{m+1}^2}}{2} \ell \tag{5}$$

The flow was assumed to be uneven, flowing in a non-prismatic channel (both the width of the stream and the depth along the length of the watercourse change).

$$z_m - Q^2 \frac{1}{K_{aver}^2} = f(z_m) \tag{6}$$

Thus, the equation is solved by the selection method. The results of the depth calculation in the alignment 1 are presented in Table 2. The distance X is assigned following the equation of the flow's turbidity distribution along the length, depending on the previously assigned degree of clarification of the flow.

3 Results and discussions

We will calculate the deformation for two variants:
Option 1: Fully clarified flow, $\varepsilon = 1 - S_{dam}/S_{tr} = 1$; where S_{dam} is the average turbidity of the flow in the dam alignment; $h_f = 3000$ *m*.
Option II: $\varepsilon = 0.8$; $h_f = 1700$ *м*.

For a conditional settlement period of 10 years in length, compiled taking into account the table.1. and the UGMS (Department of Hydrometeorological Service of the Republic of Uzbekistan) data on the water content of the Amudarya River for the period from 1999-2010 (medium-water year + high-water +low-water + 2 medium-water + 3 high-water + 2 medium-water + low-water), i.e., the repeatability (periodicity) of different water years is taken into account.

Also, the calculation is carried out provided that the first year in the calculation series will be high-water or low-water for the month with the maximum consumption equal to Table.1 $Q = 580$ m^3/s, and the period with the maximum flow rate according to the 2004 hydrograph $Q_{max} = 1800$ m^3/s and the 2010 hydrograph $Q_{max} = 2500$ m^3/s (June 2010)

The calculation also used:

1. The slope of the watercourse $i = 0.00008$ (according to the expeditions of the Karakalpak branch of the Central Asian Institute of Irrigation (Institute of Water Problems and Irrigation) in 1998-2010)
2. $L_2 = 20000$ *m*; $L_1 = 3000$ *m* (for option I) and $L_1 = 1700$ *m* (for option II);
3. $\gamma_1 = 1000$ kg/m^3, $\gamma_2 = 2500$ kg/m^3;
4. the roughness coefficient was assumed to be equal for finely sanded soils $n = 0.030$.

As studies of the general erosion in the lower reaches of the Takhiatash hydrocomplex (located above the considered section) have shown, in the first years of operation of the hydroelectric complex, the channel is more susceptible to the process of erosion than in subsequent years with the same initial data (*Q,h,b*). That is, over time, the channel becomes more stable. Thus, the sequence of different water years becomes extremely important. According to the calculations carried out, the lowering of the bottom in the first ten years (including years of different water content following the order of the actual hydrological series of 1991-2016, the average flow rate for the period is 150 m^3/s), provided that the

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width of the channel in the lower reaches is constant, is expected to be *0.17-0.41 m* (with full flow clarification) and *0.16-0.38 m* (with partial flow clarification $\varepsilon=0.8$).

Table 2. Initial data and calculation results of deformation below the Mezhdurechensk reservoir

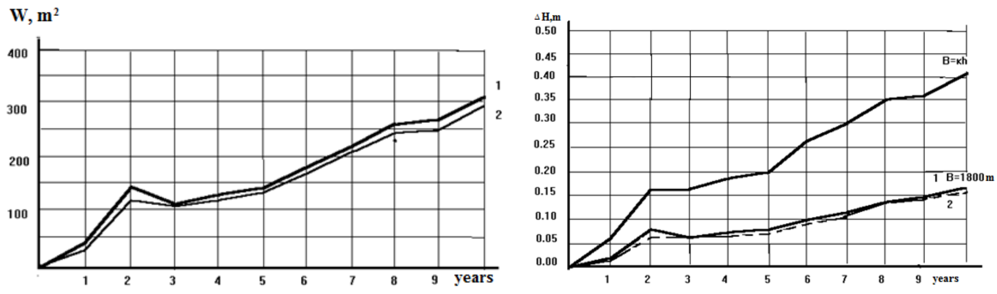
Q	initial data							calculation results				
m^3/s	**section line** 1				section line 2		t	**section line** 1		section line 2		
	B_1	h_1	B_{given}	H_{given}	B_2	h_2	10^5 sek	z	w	Z_{given},m	z_f, m	w, m
Option I												
67	1800	0.75	461	2.93	283	0.87	315	0.05	20	0.06	0.02	40
150	1800	1.15	562	4.02	330	1.28	630	0.14	66	0.16	0.08	140
100	1800	0.94	492	3.44	306	1.05	945	0.14	62	0.16	0.06	110
90	1800	0.88	483	3.28	300	1.00	1260	0.15	65	0.18	0.07	125
85	1800	0.87	481	3.27	297	0.98	1575	0.17	73	0.20	0.08	146
110	1800	0.99	499	3.57	312	1.10	1890	0.22	100	0.26	0.10	184
125	1800	1.06	509	3.75	300	1.17	2205	0.26	121	0.30	0.18	220
140	1800	1.13	518	3.92	327	1.24	2520	0.30	144	0.35	0.14	255
130	1800	1.08	512	3.80	322	1.19	2835	0.31	147	0.36	0.15	263
150	1800	1.17	524	4.02	331	1.28	3150	0.35	171	0.41	0.17	304
33	1800	0.51	413	2.22	248	0.62	315	0.03	11	0.04	0.02	21
220	1800	1.45	557	4.69	356	1.54	315	0.11	56	0.13	0.06	103
580	1800	2.34	638	6.60	428	2.44	32	0.03	18	0.04	0.02	36
1800	1800	4.09	749	9.83	531	4.18	32	0.06	45	0.07	0.04	68
2500	1800	4.79	783	10.0	565	4.88	32	0.08	64	0.09	0.05	88
Option II												
67	1800	0.81	471	3.09	283	0.87	315	0.05	20	0.055	0.019	34
150	1800	1.22	529	4.14	331	1.28	630	0.14	66	0.154	0.06	111
100	1800	0.99	499	3.57	305	1.05	945	0.14	62	0.154	0.06	108
90	1800	0.94	491	3.44	300	1.00	1260	0.15	65	0.165	0.063	114
85	1800	0.92	488	3.39	297	0.98	1575	0.17	73	0.187	0.072	131
110	1800	1.04	506	3.70	311	1.10	1890	0.22	100	0.242	0.097	175
125	1800	1.11	516	3.87	320	1.17	2205	0.26	121	0.286	0.115	206
140	1800	1.18	525	4.05	327	1.24	2520	0.30	144	0.330	0.138	248
130	1800	1.13	518	3.92	322	1.19	2835	0.31	147	0.341	0.138	249
150	1800	1.23	531	4.17	331	1.28	3150	0.35	171	0.385	0.162	292
33	1800	0.56	424	2.38	248	0.62	315	0.03	11	0.033	0.012	21
220	1800	1.49	560	4.78	356	1.54	315	0.11	56	0.121	0.05	95
580	1800	2.39	642	6.70	428	2.44	32	0.03	18	0.033	0.016	29
1800	1800	4.13	751	9.90	531	4.18	32	0.06	45	0.066	0.037	66
2500	1800	4.83	785	11.0	566	4.88	32	0.08	64	0.088	0.047	85

Note to Table 2: $z_{given} = \Delta h_x(1+x/(L-x))$; $z_f=(\kappa*(h_{given}+z_f)^{1+a}) / b_f - h_f$;

The change in the cross-sectional area of the riverbed will be *304(292)*m^2. Calculations of different water years showed the following:

1) if the first year is average (*Q=33 m3/s),* then the decrease for the first year will be *0.02(0.012) m/year*; with $Q=220\ m^3/s$, the decrease will be *0.06(0.05) m/year* ;

2) calculations for deformation at maximum flood flow rates showed that at $Q=580\ m^3/s$, the erosion could reach 0.02(0.016)m during the month, and at $Q=1800\ m^3/s$, the decrease can be *0.04(0.037)m* during the month, at $Q = 2500\ m^3$/s (flood consumption in high-water 1998) *0.05 (0.047)* m during the month.



a) (b)

Fig. 1. Calculated curves resulting deformations (a) and calculated curves of lowering the average level of the bottom (b) below the Mezhdurechensk reservoir for ten years.
1 is calculated deformation curve for option I. 2 is calculated deformation curve for option II

F(w), shown in Fig.1 (a), is the resulting curve of the deformation areas of the cross-section of the channel; in Fig.1 (b), the chronology of the change of Δz in time over the calculated period is presented, provided that the width of the channel behind the dam is constant $B=1800\ m$: $\Delta z=0.17\ m$ for ten years; and provided that the width narrows to a stable width $B_{stable}=kh^a$: $\Delta z=0.41\ m$ (with the concentration of the flow at a narrower width, the decrease will be correspondingly large).

4 Conclusions

1. To calculate the total erosion of the channels after flow regulation, a method based on theoretical equations of channel deformation (Saint-Venant equation) was applied. Since empirical methods were more widely used for the conditions of the Amu Darya River, empirical dependences were used to solve the deformation equation to determine the transporting capacity of the stream under conditions of its clarification after flow regulation and the relationship between the width of the deformable channel and the depth.

2. For calculations, a hydrological series was modeled based on the available in-situ data on the actual discharge of water from the Mezhdurechensk reservoir in different water years (including different water years following the order of the actual hydrological series 1991-2016, the average flow rate for the period is $150\ m^3/s$).

3. The results of calculating the total erosion of the bottom in the first ten years of the simulated hydrological series of years, provided that the width of the channel in the lower reaches is constant, is expected to be *0.17-0.41 m* (with full flow clarification) and *0.16-0.38 m* (with partial flow clarification $\varepsilon=0.8$). The change in the cross-sectional area of the riverbed will be $304\ (292) m^2$.

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